TITLE: Imaging Technologies in the Millimeter Wave Region

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Abstract - Imaging technologies using millimeter (mm) waves offer unique measurement means in many application areas. We discuss here mm-wave focal plane imaging technologies whose resolution is limited by diffraction amd also mm-wave scanning near-field microscopy whose resolution is much smaller than operating wavelength. Results of our researches on both of these imaging technologies are presented.

1. MM-wave Imaging

Millimeter wave focal plane imaging [1] is able to provide image information through clouds, smoke, and dust when visible and IR systems are unusable. It can also be used in the fields of plasma measurement, remote sensing, etc. The resolution of the focal plane imaging is limited by diffraction and is the order of wavelength, while scanning near field microscopy achieves sub-wavelength resolution [2], which offers other applications of millimeter wave imaging technologies.

2. Focal plane imaging (Imaging arrays)

Conventional millimeter wave imaging relies mainly on the use of a single detector, with the optics mechanically scanned to obtain an image. The use of multiple detectors in an imaging array, however does not require mechanical scanning and makes real-time imaging possible. Figure 1 shows a 60 GHz imaging array [3,4] which consists of 2-element Yagi antennas with beam-lead Schottky diodes at the center of the antennas. The interval between the antennas was determined by the sampling theorem to obtain the diffraction-limited image.

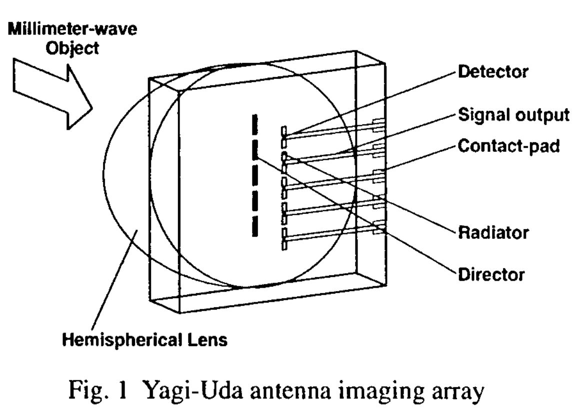

Fig. 1 Yagi-Uda antenna imaging array

i) Plasma diagnostics

The optics for mm-wave imaging radar systems can be designed using the ray tracing method. Figure 2 shows the 70 GHz optics designed for measuring 2-dimensional plasma density profile in a plasma machine for nuclear fusion research at the University of Tsukuba. Figure 3 shows measured time-revolution of 2-dimensional plasma density profile [5].

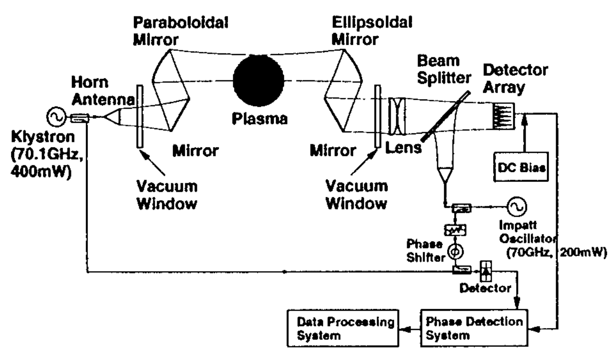

Fig. 2 Phase imaging system for plasma diagnostics

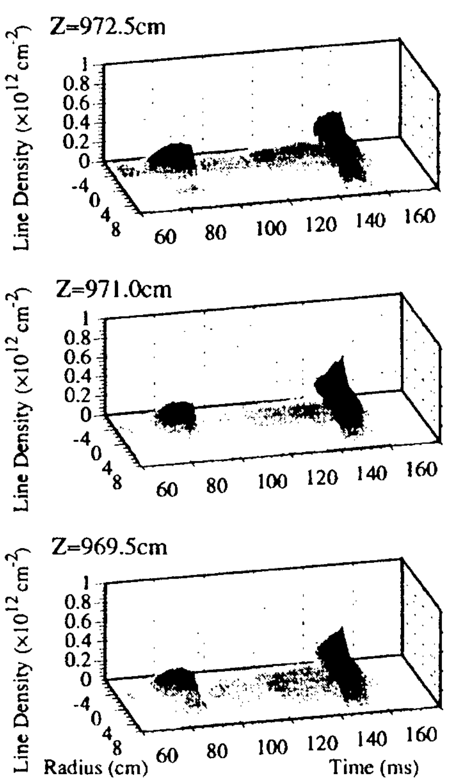

Fig. 3. Time evolution of line density radial profiles at three axial positions of a plasma at Tsukuba.

ii) Millimeter wave images and neural network processing

A neural network signal processing has been successfully introduced to recognize mm-wave images which were distorted by speckle and/or glint through coherent illumination [6].

Alphabetical letters made of aluminum foil were used as test objects for evaluating our mm-wave imaging system. Figure 4 (a) shows experimentally-obtained images for the letters A and J. The size of each object corresponds to about 8 x 8 pixels on the image plane. The images represent power distribution of scattered signals and are strongly distorted, mainly because of speckle and/or glint resulting from coherent illumination.

To recognize these images, a feed-forward neural network was used as a signal processor. The network consists of 10 x 10 input units, 60 hidden units and 26 output units. In Fig. 4 (b) the recognition rate is shown as a function of the number of "teach-data" required, when 10 alphabetical letters (A, H, J, L, O, P, S, T, V, and Z) which are dissimilar to each other were used as the objects. A high recognition rate of 98 % has been obtained using data from five teaching trials for each letter, which shows that neural network signal processing is a very powerful tool for recognition of mm-wave images.

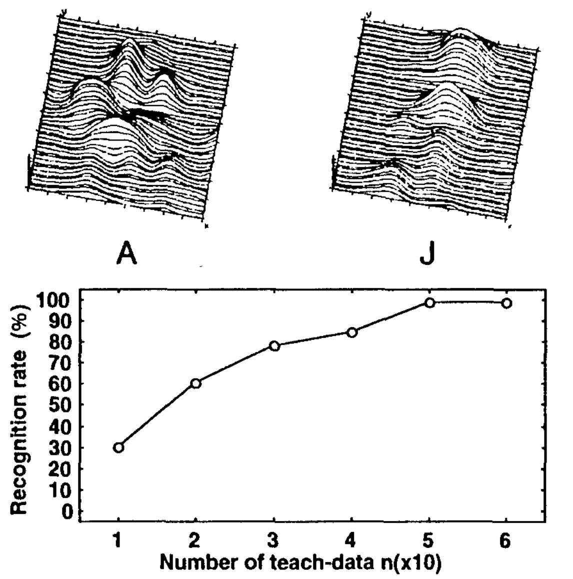

Fig. 4. Typical examples of MM-wave images for the letters A and J (above), and recognition rate as a function of the number of teach-data (below).

3. Scanning near-field microscopy

Diffraction limits the resolution of focal plane imaging and conventional microscopy to approximately $\lambda/2$. Sub-wavelength resolition has been demonstrated with scanning near-field microscopes. We proposed and demonstrated a new type of scanning near-field millimeter-wave microscopy using a metal slit at the end of a rectangular waveguide as a scanning probe [2, 7, 10]. The waveguide probe is shown in Fig. 5. A reduced-height waveguide forms the slit; the wide dimension of the slit and that of the waveguide are identical, but the waveguide height is reduced down to $\lambda/60$ (80 μm at 60 GHz).

This probe is operated above the cutoff frequency for the fundamental waveguide mode and thus provides much stronger signals than point-type probes which operate below the cutofff frequency, resulting in improved sensitivity or resolution. For a 60 GHz band probe with the slit width of 80 μm the power transmission coefficient was estimated as 20 % which is much larger that that (10^{-5} %) for conventional metal-coated, tapered optical fiber probes. Also the slit type probe makes fast (but rough) scanning over a wide sample possible when it is useful.

To achieve sub-wavelength resolution for all directions with the slit-type probe, we have adopted an image reconstruction algorithm based on computerized tomographic imaging such as that used in the x-ray CT imaging.

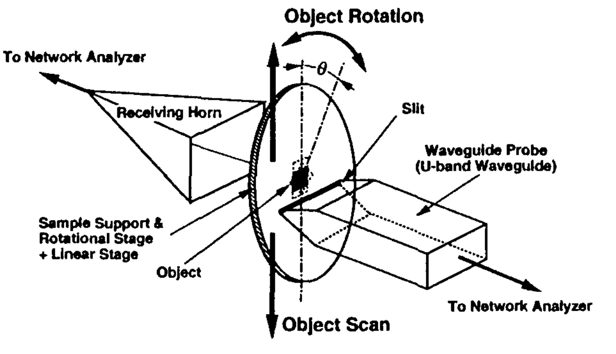

Fig. 5 Scanning near-field microscopy using a slit type probe.

We have successfully demonstrated an application of the microscope with a slit type probe in visualization of transition phonomena of photoexcited free carriers in a silicon substrate, i.e. time-resolved imaging of carrier distributions. For this demonstration a high-speed homodyne detection system at 60 GHz with a response time of 0.4 ns was constructed. The experimental setup of showing the probe and the substrate is depicted in Fig. 6. The object was a silicon on quartz (SOQ) sustrate. The thickness of the silicon and quartz layers were 0.2 μm and 1.2 mm, respectively. Optical pulses from a Q-switched Nd:YAG laser passing through the quartz layer generated free carriers in the silicon layer. The photoexcited area was 0.5 mm in diameter. The density of free carriers generated was estimated to be as high as 10^{+17} / cm^3. Figure 7 shows the temporal revolution of the carrier distribution. Free carrier generation and diffusion processes are clearly imaged [8-10]. The images show that the carriers generated diffuse non-uniformly in the silicon layer, which suggests that the layer has some defect distributon along

the surface. The life time of carriers is affected and determined by the defect distribution. Animation of the images in Fig. 7 can be seen in our Web site [11].

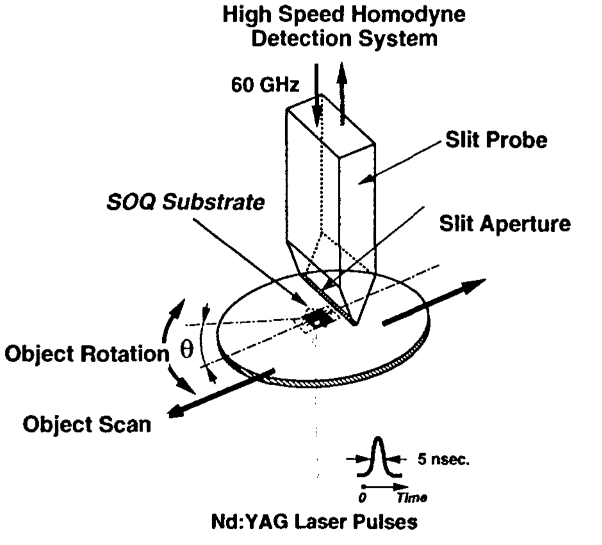

Fig. 6 Experimental scheme for measurement of photoexcited free carriers in a Silicon-On-Quartz substrate.

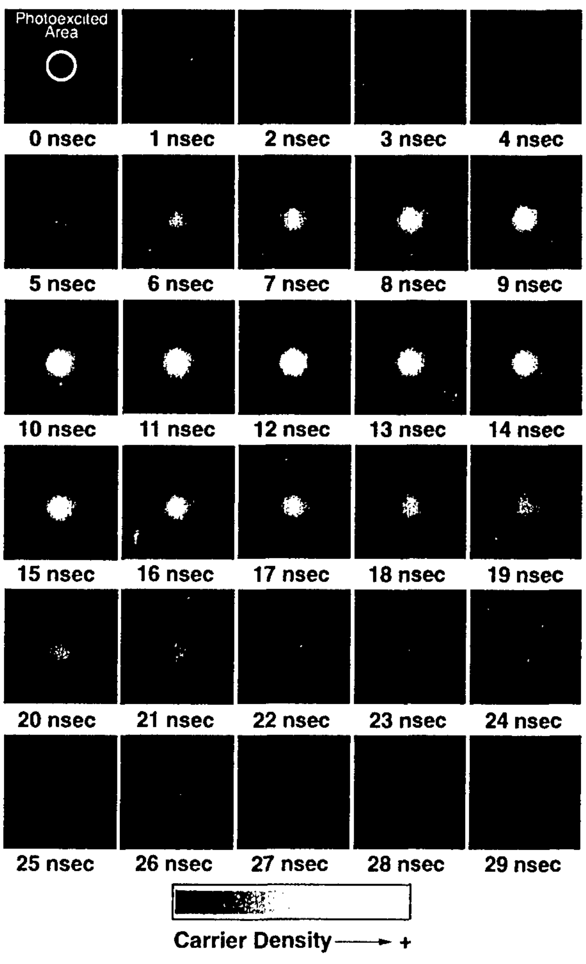

Fig. 7. Temporal evolution of photoexcited free carrier distribution. The time interval between the figures is 1 ns and the circle in the image at 0 ns shows the region illuminated by a laser.

4. Summary

As the proverb of "Seeing is believing" says, imaging technologies provide wide information. The unique characteristics of millimeter wave propagation make mm-wave imaging technologies very atractive.

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